PRELIMINARY NOTE: THE INFLUENCE OF CHANGES OF ILLUMINATION UPON AFTER-IMAGES

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The conditions under which the quality and duration of after-images can be studied are so extremely varied that generalizations concerning the after-image process have little value in the absence of a detailed control and specification of these conditions. For this reason, I undertook, several years ago, the investigation of after-images produced under very special, but carefully controlled conditions, in the hope of obtaining consistent results. At an early stage in the research, I found that such results could only be secured when the effective aperture of the pupil was kept constant, because the character and life of an after-image depends not only on the momentary nature of the retinal stimulus, but upon the variations which this stimulus undergoes.

In all of the measurements to be considered in this paper, an artificial pupil, 2.36 mm. in diameter, and registered with respect to the line of sight by a device which I have described in another place, was employed. The after-image was produced by preëxposure of the rested retina of one eye to a semi-circular field, fixation being directed to a point in the center of the diametric boundary. The after-image was always observed by projection upon a complete circular field of the same quality as the semi-circular stimulus, fixation being maintained on the center of the circle, so that the conditions of observation were similar, in general, to those presented by a simple bipartite photometer field. In all cases, the surroundings of the test area were objectively dark, and the wave-length constitution and photometric brightness of the stimuli were carefully determined in absolute units.

Under these conditions, the mean variation of the time of decay of an after-image, for a single trained subject, is about 8%. It is not my intention to discuss here in detail the results of numerous measurements of the duration and intensity of after-images of this sort, made with a wide range of wave-lengths, and stationary intensities. It will suffice to say that

the duration is nearly independent of wave-length, and of absolute intensity, but varies radically with the diameter of the field and with the individual, as well as with the preëxposure time. Decrease of the stationary intensity below 10 photons (10 candles per square meter with a one square millimeter pupil) lowers the duration, and there is also a slight tendency for it to be lower in the red end of the spectrum than in the blue end. Increase of the preëxposure time above 100 seconds causes practically no increase in the duration. For myself, using a 1¼° foveal field, the maximal duration[1] varies from 70 seconds in the red to 95 in the violet.

In view of the slight influence of the magnitude of the fixed intensity, the remarkable effects produced by intensity variations in the reacting field, are of great interest. These effects may naturally be classified into two groups, those due to dimming and those due to brightening of the field. Hering and his pupils have made considerable use of dimming phenomena in their experiments to support the theory of antagonistic colors.[2] The recent very interesting studies of G. H. Miles—published since my results were obtained—on "The Formation of Projected Visual Images by Intermittent Retinal Stimulation"[3] undoubtedly bear upon the same fundamental processes.

If an after-image, formed and projected in the manner already described, be permitted to fade, and if then, the after-image of the projection field itself be observed against a completely dark ground, a demarcation of the field into halves can generally be noted. This effect is always obtained with short preëxposures and high intensities, but is absent for preëxposures which approach in duration the "equilibrium time," or maximal duration of the image.

If the intensity of the projection field is decreased, but not made zero, a similar but usually far more striking rejuvenation of the after-image contrast, occurs. The preëxposed half appears darker and more or less complementary in hue as compared with the other half of the field. In its general form, the principle that *dimming the reaction light enhances the processes which are "antagonistic" to the original stimulation,*

[1] The duration increases asymptotically with increase in the preëxposure time. For a discussion of this law, see L. T. Troland, Apparent Brightness; Its Conditions and Properties. *Transactions of the Illuminating Engineering Society,* XI, 1916, 947-967.

[2] See *e. g.,* R. Dittler, and Satake, Eine Methode zur Bestimmung der gegenfarbig wirkenden Wellenlangen des Spektrums. *Zeitschrift für Sinnesphysiologie,* XLVIII., 1914, 240-252.

[3] British Journal of Psychology, VII., 1915, 420-434.

is familiar to all readers of Hering. However, in order to account for the increase of the after-image contrast, the principle must have a special mathematical form, since if dimming affected both halves of the field equally, the contrast would not be augmented, however great the absolute alteration of the compared areas. Consequently, it is necessary to state that a very slight difference in the level of fatigue of two visual areas furnishes the condition for a large difference in the magnitude of the *dimming effect* producible on these two respective areas. This is the principle of the *dimming contrast effect.*

An explanation of this somewhat extraordinary principle is suggested by further study of the phenomenon itself. The contrast, which has been reëstablished by dimming, fades quite rapidly on the dimmed field, but if—after it has disappeared—the field is brightened to its original intensity and then dimmed once more, the contrast returns; a process which can be repeated successfully over a period sometimes twelvefold the life of the image on the undimmed field. This factor of the relative *durability*[4] of the dimming contrast effect decreases rapidly to an asymptote with increase in the original preëxposure time; in other words, the effect is less marked in conjunction with a generally low level of visual sensitivity than it is with higher levels. Increase in the degree of dimming reveals a maximum of the "durability" of the effect in the neighborhood of one-half the primary intensity. From $100\,\sigma$ to $600\,\sigma$ the durability increases practically as a linear function of the time during which the dimmed intensity is maintained at each successive test. Between .7° and 3.5°, a linear relationship exists between the durability and the diameter of the stimulus field. When the primary intensity is varied, and the dimming is always to a constant fraction of this intensity, the effect shows a maximum in the neighborhood of 100 photons, depending on the value of the fraction. This law also applies to the maximal duration of the dimming contrast in the dimmed phase, if this is prolonged. The latter duration decreases asymptotically to zero in successive intermittent dimmings.

Certain of the above facts strongly suggest that the dimming contrast effect depends upon a difference in the rate of decay

[4] The "durability" is to be distinguished from the "duration" of the effect, the former term referring to the period during which it can be obtained by repeating the process of dimming (and brightening), the latter designating the life of the image in a single cycle of illumination change.

of some component of the excitation in the contrasted fields, this decay taking place more rapidly in the more fatigued area. In other words, the more fatigued area shows a lessened resistance to change in its state of excitation. The dimming contrast, on this theory, should be in evidence only *during* the change, and the fading of the contrast would indicate that the change had been completed in both halves of the field. On the other hand, if the change were repeated, by brightening and redimming the field, the contrast would reappear, but would persist a shorter time than before, because of the nearer approach of the resistance factors of the two halves, to equality. This explanation applies to both the chromatic and the achromatic aspects of the phenomenon.

The assumption that exposure of a visual area to stimulation decreases the resistance which it offers to change in its state of excitation is in harmony with the laws stated by Helmholtz for the duration of positive after-images,[5] and is also borne out by the remarkable effects produced by *brightening* of the field under the general experimental conditions above described.

When the field is brightened, in general the faded negative contrast is *reversed,* and becomes *positive.*. The preëxposed half appears brighter than the non-preëxposed half, and becomes more saturated than the latter, which tends to acquire a hue complementary to it. This *reversal effect,* or brightening contrast effect can be obtained either by brightening on the basis of the primary stimulus intensity, or by dimming, permitting the dimming contrast to fade, and then restoring the primary intensity. The positive contrast fades rapidly on the brightened field, but—as in the case of the dimming contrast—can be rejuvenated by repeating the cycle of operations. With a spectral red stimulus, the total durability of the reversal effect, seems to be of the same general magnitude as that of the dimming contrast effect, when the field is alternately dimmed and brightened with equal intervals. To obtain the reversal contrast at its maximum, it is necessary to permit the preceding dimming contrast to fade completely, and *vice versa.*

I have made a number of careful studies on the laws governing the duration of the reversal contrast after any single brightening, when the bright phase is prolonged. In these experiments, the reversal was obtained by first dimming the primary intensity and then brightening it again, after an interval. It was found that the duration of the contrast increased to a maximum as this interval was lengthened, and then

[5] Handbuch der physiologischen Optik, 3te Auflage, 2, 1911, 194-202.

decreased asymptotically to zero. A similar law was found to connect the duration with the dimmed intensity, a maximum occurring for a dimming to about 1/50th of the original value. Variation of the preëxposure time also produces a maximum, and an asymptotic fall with the higher preëxposures (under the conditions which I employed, above 20 seconds). Other things equal, the effect is much more marked on large than on small fields.

These correlations are consistent with the view that the reversal of the negative after-image caused by brightening of the projection field, also depends upon a lessened resistance to change in state of excitation, due to preëxposure. The reversal, like the dimming contrast, persists only during this change, but can be rejuvenated by repeating the cycle of operations. In other words, the two phenomena are obverse and reverse of the same underlying condition. I do not claim that there are no difficulties to be met by this view, but it offers the most satisfactory synthesis of the facts that I have yet been able to find.

One difficulty lies in the manner in which the two effects vary with the wave-length of the stimulus. I have thus far not made searching experiments on the influence of wave-length upon the dimming effect, but cursory observations with representative spectral colors have not shown any marked influence of this factor. The dependency of the reversal phenomenon upon wave-length, however, appears to be quite clear cut. When the intensity change employed has a 10:1 ratio, the reversal is obtained at very low intensities in the red end of the spectrum,[6] but as the stimulus moves towards the blue end, higher and higher primary intensities are required, and the effect is absent beyond the green under all conditions which I have tested systematically.

The colors and color contrasts generated in the dimming effect are extremely vivid and variegated. In general, as would be expected, dimming tends to move the apparent color of the field along the spectrum towards the complementary of the "real" color. The spectral distance moved through increases with increase in the fractional dimming, with increase in preëxposure, and with decrease in the primary intensity. The direction of movement[7] in the spectrum, as well as the distance, varies with the wave-length of the stimulus. From

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[6] These experiments were carried out at the Nela Research Laboratory.

[7] Direction of movement is determined by use of a graded series of values of the governing variables.

the extreme red to the yellow the change occurs through the purples; between the yellow and yellow-green there is reversal of the direction; between green and blue-green a further reversal; between blue and violet a third change; and between violet and extreme red, again, a fourth shift in direction. These facts indicate that there are four points in the color circle, for which dimming would produce only a saturation change, unless it could suffice to produce the complementary. In all cases the color contrast fades far more rapidly than does the luminosity contrast. It will be observed that all of these relations are in harmony with Hering's general schema of the visual qualities.

Although certain aspects of the dimming and reversal phenomena are explained by Hering's assumptions, these assumptions are by no means sufficient. Moreover, general physiological objections to Hering's doctrine of sensory metabolism make it illegitimate to employ his hypotheses in the exact form in which he stated them. However, my attempt to modify his views[8] so as to meet these objections yields postulates still less adequate, so far as the dimming and reversal effects are concerned, although they satisfy the laws for fatigue with stationary illumination much better than do Hering's original conceptions. My present opinion is that the former effects depend either upon the laws governing certain of the "constants" or parameters of the simple equations for retinal excitation, or else that they rest upon conditions in the visual system posterior to the retina.

I have met with some success in an attempt to explain them as a result of *Bahnung,* or the reduction of synaptic resistance by excitation. On this basis, the rate of change of excitation in a synapse may be conceived to be proportional to a force factor, representing the intensity of the incoming current, and inversely proportional to a resistance factor, representing the susceptibility of the synapse to alteration of its state. This makes the excitation an exponential function of the time after any change in the force factor, and of the resistance. The resulting equations meet many aspects of the experimental situation in a satisfactory qualitative way. However, at present, I regard this theory as highly speculative.

In connection with the above, I wish to mention several phenomena upon which thus far, I have made no detailed quantitative studies. In the first place, by use of the dimming procedure, after-image contrasts can be obtained which endure

[8] L. T. Troland, Adaptation and the Chemical Theory of Sensory Response. *American Journal of Psychology,* XXV., 1915, 500-527.

three or four minutes, on the basis of only an eighth of a second difference of exposure of the two halves of the field. I have been unable to secure these contrasts with red light, but they are easily produced with blue. Under these conditions, positive contrasts, or reversals, are sometimes obtained during the dim phase. Another interesting effect is the spontaneous appearance of a reversal, immediately following the disappearance of an ordinary negative contrast (through fading), without alteration in the intensity of the field. This effect is obtainable with all of the spectral colors, but most easily with the end-regions of the spectrum, and with short preëxposures. It is also possible to produce a positive image as an initial result of preëxposure, when the blue end of the spectrum (especially the blue-green) is employed and the preëxposures are less than 16 seconds.